General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

DK 621.455.038.056
662.612.1
547.388+546.175-323

DLR FB 68-85

STUDIES ON THE EFFECT OF FUEL INJECTION ON THE IGNITION PROCESS OF THE HYDRAZINE-NITRIC ACID SYSTEM

(Untersuchungen zum Einfluss der Treibstoffeinspritzung auf den Zundvergang am System Hydrazin - Saltpetersaure)

Deutsche Forschungstanstalt fur Luft- und Raumfahrt (DFL)
Institute fur Strahltriebe
Inst.-Teil Chem. Raketentriebe

Braunschweig, 12/12/1968

Institute Director:

Prof. Dr. Otto Lutz (Entineer)

Insttite Section Leader:

Winfried Buschulte,
(Certified Engineer)

AUTHOR

HARALD TWARDY (Certified Engineer)

Translated by the Center for Foreign Technology
Pasadena, California, on 28 June 1969

Prepared for and issued by the Jet Propulsion Laboratory,
California Institute of Technology, Pasadena, Calif.
under NASA contract NAS 7-100.

Contents

2. Nomenclature

α	$\left[\frac{\text{Joule}}{m^2 \cdot sec \cdot grd}\right]$	heat transfer coefficient
β	[°]	angle between the propellant streams (nozzle angle
D	[m]	diameter of the volume element; in special cases, that of the propellant stream
$\mathfrak{D}$	$\left[\frac{m^2}{sec}\right]$	diffusion coefficient
E	$\left[\frac{\text{Joule}}{kmol}\right]$	combustion energy of the reaction
F	[m^2]	surface of the volume element
f(c)	$\left[\frac{kmol}{m^3 \cdot sec}\right]$	a function of the time-dependent concentration which is independent of temperature, and, in this case, should be constant
h	$\left[\frac{\text{Joule}}{kg}\right]$	enthalpy
L	[m]	nozzle length
P	$\left[\frac{N}{m^2}\right]$	pressure
Q	$\left[\frac{\text{Joule}}{kmol}\right]$	heat of reaction
q	[Joule]	amount of heat
$\dot{q}$	$\left[\frac{\text{Joule}}{kg}\right]$	heat resulting from change in thermodynamic conditions
R	$\left[\frac{\text{Joule}}{kmol \cdot grd}\right]$	general gas constant
T	[°K]	temperature

t	[sec]	time
x	[m]	layer thickness
V	[m^3]	mixture volume
v	$\left[\frac{m^3}{kg}\right]$	specific volume
Ω	[-]	mixture ratio: $\frac{\text{oxidizer}}{\text{oxidizer \& fuel}}$

Indices

OX	oxidizer
BR	fuel
chem	chemical reaction
o	environment
V	loss

1. The Problem

In the starting operation of a new liquid-propulsion rocket for test purposes, pressure peaks -- so-called ignition shocks -- appeared repeatedly during the ignition phase. Ignition was obtained with the hypergolic propellant combination of hydrazine-nitric acid under ambient conditions. Since ignition shocks must be avoided in a combustion chamber equipped for test purposes with larger quartz windows, an investigation of the cause of this phenomenon was urgently required.

It was found that, in this case, unusually great ignition delays occurred, during which the combustion chamber became charged with propellant. The study which follows is therefore concerned with the effect of the mechanical preparation of propellants on the ignition process, which -- aside from other influences -- plays an important part in the generation of ignition shocks. The investigations were conducted using an impinging-stream element under ambient conditions, with particular emphasis on the propellant combination of hydrazine-nitric acid, as compared with hydrazine-N_2O_4, UDMH-N_2O_4, and A-50/NTO.

2. Nomenclature (On Preceding Page)

3. Recent Studies of the Problem of Ignition Shock

In connection with the relationship between the mechanical preparation of propellants and the ignition delay investigated by DFL, new American studies concerning the problem of ignition shock are referred to. Most recently, this problem received particular attention because of the frequently observed appearance of pressure peaks during re-ignition, particularly of pulse-propulsion engines. In such motors, it could be determined without question that nitrates of the propellants used had formed on the combustion chamber wall after cutoff (Refs. 2, 3). The fuels hydrazine, monomethylhydrazine, UDMH, and A-50 with the oxidizer N_2O_4 were investigated. Among the resulting nitrates, hydrazine nitrate has the greatest explosive action while, at the same time, having the least sensitivity to shock. The least sensitive is ammonium nitrate, which was formed when UDMH was used as fuel. An incomplete reaction process or decomposition of fuel residues is assumed to be the cause of the formation of such nitrates in the motors, the residues entering the combustion chamber from the outer chamber of the injector head even after propellant cutoff when the valves are shut off. The fact that the nitrates were sometines found on the combustion chamber wall in aqueous solution speaks for this latter theory. In a subsequent ignition, the accumulated nitrate

mass will necessarily be dissociated more or less forcefully, depending on its amount and chemical composition, and cause a pressure peak in the combustion chamber. The possibility that such nitrates may be formed even during combustion in colder combustion chamber areas or on the even cooler chamber walls is also not excluded (Refs. 3, 4). These, however, decompose again during the combustion process in the chamber and therefore have no effect on ignition.

The appearance of ignition shocks during the ignition process in vacuum is also well known. F. A. Boorady et al. (Ref. 5) describes his studies of this problem, which were necessitated by the failure of the Gemini Agena 6 satellite experiment. J. A. Simmons et al. (Ref. 6) cites two possible causes for the appearance of ignition shocks under space conditions, which may occur simultaneously. During the escape of the liquid fuel into the vacuum of the combustion chamber, the rapid expansion of the evaporating or prereacting fuel results in a drop in temperature, which makes ignition difficult. At times, freeze-out even causes a solid coating to form on the chamber wall. The example of hydrazine-N_2O_4 shows further that the prereaction can take place under other than ambient conditions and normal temperature. The prereaction that occurs here obviously appears to be less exothermal, so that ignition follows only after the pressure and temperature in the chamber have been increased by considerable amounts of fuel. A sudden combustion in the noew overloaded chamber then causes the pressure peak.

4. Heat Budget During Ignition

Part of the heat liberated during the prereaction will now be used for heating the reaction partners to ignition temperature, since a simultaneous heat loss to the environment can no longer be avoided. AS long as the remaining heat is great enough to cause heating to the ignition temperature, ignition will take place with more or less delay. Even this indicates that the ignition delay cannot be considered separately from the injection system. The ignition delay values determined in a certain system can therefore not be transferred to another system but must be used as reference values only.

According to the heat-explosion theory, the temporary heat production of a mixture volume V, as a result of chemical reactions, amounts to

$$\frac{dq_{chem}}{dt} = V \cdot Q \cdot f(c) \cdot e^{-\frac{E}{R \cdot T}} \qquad (4.1)$$

The simultaneous heat loss of the reacting volume is

$$\frac{dq_v}{dt} = \alpha \cdot F \cdot (T - T_0) \,. \qquad (4.2)$$

The remaining heat -- usable for ignition -- is, therefore,

$$\frac{dq}{dt} = F\left[\frac{V}{F} \cdot Q \cdot f(c) \cdot e^{-\frac{E}{R \cdot T}} - \alpha (T - T_0)\right] \qquad (4.3)$$

Since $V/F \approx D$ and $\alpha \approx 1/\sqrt{D}$ (Ref. 7), with D the diameter of the volume element, the expression in brackets becomes zero or negative below a certain diameter; that is the ignition delay becomes infinite. To induce ignition, then, a minimum amount of reactive components is required. Otherwise, the ignition delay is lessened with increasing reaction heat and falling activation energy -- as can be seen from the above equation -- the greater the reaction velocity and the lower the ignition temperature.

Clusius (Ref. 8) describes the process of heat development during prereaction in a model, using coarse mixing as a basis. This causes boundary layers to be maintained between oxidizer and fuel, so that the mixing or solution of the two liquid components during the prereaction can be controlled by the diffusion process. The heat liberated at the first contact with the boundary layer is transferred to adjacent layers of liquid by heat condution. Only after a final layer thickness liberates enough thermal energy through sufficient heating in the prereaction and can compensate at least for the heat dissipated to the surroundings does the secondary reaction (ignition) set in. From the root-mean-square displacement $x^2 = 2 \cdot \mathfrak{D} \cdot t$ for molecular diffusion, the resulting layer thickness x can be approximately determined. With diffusion constant $\mathfrak{D} \approx 1 \cdot 10^{-5}$ cm^2/sec for liquids and an ignition process of 50 msec, a layer thickness up to onset of ignition of 0.01 mm results.

In vacuum, ignition can be assured only if the heat removed from the prereaction products by expansion can be sufficiently replaced by the primary reaction. It is known that

$$dh = dq + v \cdot dP \,, \qquad (4.4)$$

so that $dq/dt > v \cdot dP/dt$ would have to be the case in order for $dh/dt > 0$ (Ref. 6).

As we have seen, the temporary heat development of the prereaction is a decisive factor in the ignition delay. Aside from the very significant chemical parameters, the mechanical propellant preparation through the injection system also plays an important role in relation to the physical parameters, such as diffusion, viscosity, and surface and boundary-layer tension.

5. Test Setup and Procedure

5.1. Ignition Apparatus

Current tests are being conducted with specially constructed ignition

equipment (Fig. 9), whose nozzles can be exchanged and set for different injection angles. Thus, the angle between the fuel and oxidizer streams can be regulated step-wise by 15^{o} from 15 to 90 and to 120^{o}. The nozzle base diameters are 0.8, 1.0, 1.2, and 1.5 mm at a length-to-diameter ratio L/D = 10. In order to be able to direct the propellant streams against each other after a change in nozzles, the nozzle heads can be adjusted by turning during assembly. The proper postion is checked in a simple water test. After the subsequent attachment of the propellant ducts, the adjustment can no longer be changed. The free stream length is only 15 mm, so that an inadmissible stream expansion is avoided. Spengler (Ref. 1) has made ignition tests with a free stream length of 4.8 cm at injection pressure drops up to 0.7, and could scarcely detect a measurable effect on the ignition delay even at 11.4 cm. A photo-cell (Siemens APY 12 II) set to the impingement point of the streams, whose maximum spectral sensitivity is in the infrared region (1.9µm), registers the ignition time. A casing can be flange-connected to the ignition apparatus for testing the ignition behavior when there is a turn in the chamber (Fig. 11).

5.2. Measuring Procedure

Ignition delay was measured at various angles between the streams, at several nozzle base diameters, and using different injection nozzles. In one series of measurements, the injection pressure of only one component was changed at a time and the pressure of the others held constant. This caused the mixture ratio to change at constant fuel pressure as well as at constant oxidizer pressure in the range of approximately Ω = 0.3 - 0.6.

Through automatic electronic switching, the fuel component whose injection pressure is varied has enough lead time before the second component to build up the full injection pressure. The moment of pressure rise of the second component, which is introduced under the same pressure conditons, is used as the arbitrary null point for the measurement until the start of ignition (Fig. 8). The true ignition delay time, i.e., as measured from the moment of impingement of the two streams, is less by the constant quantity ΔZV than the measured ignition delay. Depending on nozzle diameter and pressure, ZV lies in the range of 4 to 8 msec. Since with our ignition apparatus, using the fuel combination hydrazine-nitric acid, ignition delays in the range of 100 to 900 msec were measured, no significant displacements result from the amount of the difference. On the other hand, the ignition delay values of several series of tests with more reactive fuels (e.g., A-50/NTO) that were made for comparison are in the 10-msec range, so that the difference ΔZV is of approximately equal magnitude. It must be taken into consideration, however, that neither would the trend of the curves change as a result of the constancy of the two ΔZV values during a series of tests, nor would the order of magnitude of the measured values when they are decreased by ΔZV. Besides, it must be kept in mind that the ignition delay values measured with a specific injection system cannot be transferred

to another system but can only be used for comparison. Boorady et al. (3) even uses the moment of valve opening as a point of reference in his ignition delay measurements.

6. Preliminary Results

6.1. Ignition Tests at the Injector Head Without Combustion Chamber

In tests with injector heads whose combustion chambers had been removed, no ignition occurred in many cases when the combination hydrazine-nitric acid was used. This is noteworthy inasmuch as this combination is considered very hypergolic. The temperature of the fuels in these series of tests was between 15 and 20 °C; 98% commercial nitric acid was used. In all cases in which no ignition occurred, thick, white, though nearly odorless gas clouds formed when hydrazine and nitric acid were injected together (Fig. 10). It is to be assumed that these were the reaction products of an incomplete reaction process; during the injection, a hissing sound was perceived nearby. In no case was arc-through of the gas clouds observed, although when the valves were shut ignition of the lagging propellant did occasionally take place at the impingement point of the streams. Spengler (Ref. 1) also reports on the failure of ignition to occur in the impinging stream procedure, although for less hypergolic combinations, such as H_2O_2 with aniline, furfuryl alcohol, or UDMH. The tests with hydrazine-nitric acid indicated that ignition failed to take place only under certain injection conditions. Our investigations showed an unmistakable dependence of the ignition transients of this combination on nozzle diameter as well as the angle between the streams (see Table 1).

Table 1 shows the increasing ignition transients with increasing nozzle diameter and impingement angle of the streams.

Measurements of the ignition process over a broad pressure range were entered in Fig. 1 for an impingement angle of 120° and a nozzle diameter of 1.5 mm. In the tests whose results led to the preparation of this diagram, no ignition occurred at high oxidizer pressure (above 11.5 atmospheric excess pressure) and at low fuel pressure (below 0.8 atmospheric excess pressure), which was apparently a result of the excessively high oxidizer supply. However, even at very low oxidizer pressure (below 1.8 atm. ex. press.), ignition was not sure to be obtained in all cases. On the other hand, in the ignition tests performed for the remaining diagrams using the fuel combinations hydrazine-N_2O_4, A-50, and UDMH-N_2O_4, ignition was attained in all cases over the entire pressure range represented.

In contrast to the hydrazine-nitric acid combination, no further degradation of ignition transients or non-ignition could be observed for the above propellant combinations when the impingement angle was reduced to 60° or with a minimum nozzle diameter of 0.8 mm.

In answer to the question why the combination hydrazine-nitric acid

did not produce ignition when small nozzles or stream diameters were used, reference is made to the ignition requirements discussed in Chapter 4. According to these, a minimum volume, i.e., also a minimum diameter, is required for reasons of a sufficiently large heat budget. Apparently, the preceding case fell short of this minimum diameter.

A degradation of the ignition transients, or a complete lack of ignition with decreasing impingement angle is, at first, inexplicable for the combination hydrazine-nitric acid in view of the extremely short ignition delays (5 msec) of this combination found by the drop-test method. Perhaps it is the great surface tension of hydrazine and nitrogen (Fig. 7) -- as compared with the other propellants -- that prevents the formation of sufficiently large boundary layers in which the primary reaction is introduced by diffusion. It is also conceivable that, especially at a low impingement angle and great surface tension, a stronger recoil of individual fluid particles takes place. This could, on the one hand, deprive the recoiling particles of the possibility of sufficient contact time and, on the other hand, the remaining residue volume could then fall below the minimum amount required for ignition. Spengler (Ref. 1) has already indicated the possible effect of the recoil of liquid particles with respect to ignition. Other experimental works are also known, according to which a lowering of the surface tension of the propellants led to a decrease in the ignition delay (Refs. 9, 10). We are planning our own experiments along these lines.

In comparing the ignition delay values measured by us for hydrazine-nitric acid with those of the other fuel combinations, the considerable ignition delay of this combination is evident, its values being greater by a factor of about 5 to 75 than the minimum measured values (cf. Table 2 and Figs. 1 to 5). The shortest times were measured for A-50/NTO.

The measured ignition delay values were entered over the mixture ratio even though it can be assumed, according to our investigations, that this plays only a very secondary role. Clusius (Ref. 8) represents the point of view that, for the hypergolic ignition process, the stoichiometric mexture ratio under no conditions offers optimum ignition conditions but at best the stoichiometric ratio of the primary reaction. For triethylamine-nitric acid, for example, this results in a ratio of 1:0.6 instead of 1:5! Since the mechanical fuel preparation, among other things, has a considerable effect on ignition during the injection process, the direction and magnitude of the pressure changes were entered in the diagrams. The difference in the curves for propellant lead (P_{OX} = constant) and oxidizer lead (P_{BR}), however, need not necessarily be due to this effect alone. It may also be related to the changed fuel preparation resulting from a different injection pressure environment. The problem be investigated further.

Table 3 shows that the ignition delay of hydrazine with nitric acid or N_2O_4 increases in some cases with increasing injection pressure (Figs. 1 and 4), or that it first decreases and then increases (Fig. 1).

When both injection pressures were increased, so that Ω remained constant in each case, the ignition delay first increased and then dropped (Fig. 2). With the fuel combinations UMDH-N_2O_4 and A-50/NTO, The ignition delay decreased with increasing injection pressure.

On the basis of the studies, it must in any case be stated that increasing dissociation of the fuel components certainly does not always go hand in hand with a lessening of the ignition delay. Although mixing by diffusion occurs more rapidly with a larger surface, at the same time, the ratio of the liberated to the discharged heat becomes more unfavorable (see Chap. 4). The recoil of liquid particles described by Spengler should also be mentioned again, which will then be lost for the start of the ignition process.

Thus, it is also understandable why ignition could not be achieved by increasing the dissociation if it did not even occur at low injection pressure. Similar observations have already been made earlier (Ref. 11). According to these, ignition took place more reliably with coarse mixing than with fine spraying. Ignition of the propellant only when the injection valve has been shut off also falls into this category. Clusius (Ref. 8) considers a retardation of the boiling of the primary reaction product with coarse mixing as possible, so that the product can be overheated to the ignition temperature. Strong vorticity, on the other hand, is known to cause the boiling retardation in liquids to be suspended.

6.2. Ignition Tests With Combustion Chamber

The ignition behavior of the propellant combination hydrazine-nitric acid was also studied with the addition of a combustion chamber mounted on the injection head. Measurements of the ignition delay under these conditions yielded a delay that was lower by about a factor of 10 as compared to the impinging stream test without a combustion chamber (Fig. 6). It was further determined that ignition always occurred, even in those cases in which it was not possible to achieve ignition without a combustion chamber. Ignition also took place when the chamber was filled with nitrogen gas. During the preliminary tests, a special combustion chamber was also filled with hydrogen; the ignitions were detonation-like in this case. For further study, the injection head was provided with a movable combustion chamber shroud (Fig. 12). The air space between the injection head and the shroud could be varied from 0 to 60 mm. It was the task of the variable air space to support the heat discharge, i.e., to degrade ignition. It was found, however, that ignition took place despite maximum opening of the air space. It began at the edge of the sheet-metal shroud on the injection side; with a certain position of the injection nozzle, ignition even started even at the tie rod between the injection head and shroud.

For a closer study of the wall effect, the ignition process was filmed through the combustion chamber opening on the nozzle side (Fig. 13). Because of the partly still quite high ignition delay

times, a frequency of about 500 frames per second was sufficient. The tests were based on settings at which ignition had never occurred without a combustion chamber. As can be seen in the pictures, the prereaction or ignition actually did first take place at the combustion chamber wall.

For further tests, the inner wall of the combustion chamber was coated with Teflon. Here, too, ignition appeared in those cases in which no ignition occurred in the impinging stream test without combustion chamber. A catalytic effect of the wall can therefore be excluded.

The start of ignition at the combustion chamber wall can undoubtedly be explained by the increased contact time of the propellant components as a result of the accumulation on the wall. The required minimum layer thickness (see Chap. 4) of the diffused liquids will, in this case, be reached with more certainty than in the impingement point of the two propellant stream. Furthermore, because of the accumulation of the liquid particles contained in the prereaction, better heating can be expected than in a spray field. This is also covered by the observation that coarse mixing results in more favorable ignition conditions than fine spraying. In this connection, ignition delay measurements by the drop-test method should also be remembered, which provided some results, even though ignition did not occur in the impinging stream experiment (Ref. 1).

7. Plan for a Continuing Test Program

To obtain certain ignition, the attempt will be made to ensure that it takes place in the vicinity of the impingement point of the propellant streams rather than on the combustion chamber wall in order to avoid different ignition behaviors on cold and warm combustion chamber walls, e.g., at restart. Studies of the ignition process in the impingement point of the propellant streams as well as the layers of liquid haze that are then formed will give clues to the effect of surface tension as well as the mechanism of preparation. The temperature dependence of surface tension and diffusion in a greater temperature range should also be taken into consideration. The measurement of intermediate and end-product lines during the prereaction a and ignition is another important subject for investigation. In connection with the above studies, more should be discovered about the apparently better ignition with coarse mixing, which, from the point of view of good combustion efficiency, would not be at all desirable. After these basic investigations have been performed under ambient conditions, the complex ignition problems of liquid propellants should be observed under vacuum conditions.

8. Summary

Ignition tests in the impinging stream process were performed for the purpose of investigating the effects of various injection conditions on ignition. Changes were made in the injection nozzle diameter, impingement angle of the two streams, injection pressure, and mixture ratio. The studies also included a separate injection head as well as an injection system provided with a combustion chamber shroud. Of particular interest was the propellant combination hydrazine-nitric acid; for comparison of the results, tests were also made with A-50, UMDH, and N_2O_4. The experiments were performed under ambient conditions.

In the tests with separate injection systems without combustion chamber, it was found that the propellant combination hydrazine-nitric acid achieved ignition only under certain injection conditions. The ignition transients increased with increasing impingement angle (60, 90, 120°) and increasing diameter (0.8, 1.0, 1.5 mm). The measured ignition delays were up to 75 times greater for this propellant combination than the shortest ignition delays of A-50/NTO. Raising the injection pressures, i.e., a finer spray, did not in general result in either a lessening of the ignition delay nor in ignition if the latter had not previously occurred.

When the injection system was surrounded with a combustion chamber shroud, ignition took place even in those cases in which it did not occur with a separate injection system. It could be proven that in these cases ignition took place on the combustion chamber wall. No catalytic wall effects appeared. The ignition delay times for hydrazine-nitric acid were less by a factor of 10 when a shroud was used than when it was not. Finally, a continuing test program is considered.

The author wishes to take this opportunity to thank Mr. Buschulte (Cert. Eng.) for his interest in this work and his advice on the preparation of injection nozzles. Appreciation is also expressed to Mr. Zocher (Eng.) for the execution of the electronic work, as well as to all colleagues for the detailed discussions which contributed to the clarification of several significant problems and became an integral part of this study.

9. References

1. Spengler, G., and Bauer, O. *The Ignition Delay of Hypergolic Rocket Propellants (Uber den Zundverzug hypergoler Raketentreibs toffe)*, DVL Report No. 433, Special printing from, "Brennstoff-Chemie", No. 4, April 1965.

2. Jurau, W., and Stechmann, R.C., *Ignition Transients in Small Hypergolic Rockets*, AIAA 3rd Propulsion Joint Specialist Conference (1967), AIAA Paper No. 67-515.

3. Perlee, H.E., Christos, T., Miron, Y., and James, H.K., *Pre-ignition Phenomena in Small A-50/NTO Pulsed Rocket Engines*, AIAA 3rd Propulsion Joint Specialist Conference (1967), AIAA Paper No. 67-516.

4. Reinhardt, Th. F., "Significance of Explosive Intermediates in Rocket Engine Combustion,"*AIAA Journal*, Vol. 6, No. 4, 1968, p.748.

5. Boorady, F.A., and Douglass, D.A., "Solution of the High-Vacuum Hard-Stort Problem of the IRNFA-UDMH Rocket for Gemini Agena," *Journal of Spacecraft*, Vol. 5, No. 1, Jan. 1968.

6. Simmons, J.A., Gift, R.D., and Spurlock, J.M., "Reactions and Explosions of Hypergolic Propellants in a Vacuum," *AIAA Journal*, Vol. 6, No. 5, May 1968.

7. Sitkei, G.,*(Kraftstoffaulbereitung und Verbrennung bei Diezel-motoren) Propellant Preparation and Combustion in Diesel Motors*, Springer-Verlag, 1964, p. 92.

8. Clusius,-, LFM, Report unpublished.

9. Bernard, M.L.J., *Surface Properties of Liquid Bipropellants and their Effects on the Kinetics of Ignition*, Fifth Symposium on Combustion, 1955, p. 217.

10. Panshkin, Ya. M., *The Chemical Composition and Properties of Fuel for Jet Propulsion*, Pergamon Press, 1962, p. 343.

11. Bgelhaaf,-, LFM, Report unpublished.

TABLES

1. Ignition transients of hydrazine-nitric acid

Nozzle diameter, mm	Angle between the streams, deg		
	60	90	120
0.8	OZ[1]	OZ	OZ
1.0	OZ	OZ	Ignition in a few cases only
1.5	OZ	Ignition in a few cases only	Ignition in a wide pressure range

P_{BR} = 0.8 - 8.8 atm[2]; P_{OX} = 2.4 atm[2] or

P_{BR} = 5.1 atm[2] P_{OX} = 1.8 - 11.5 atm[2]

[1] Abbreviation for "without ignition"
[2] Atmospheric excess pressure

2. Measured ignition delay regions of various propellant combinations

Propellant combination	Minimum ZV, msec	Minimum ZV, msec	Ignition conditions
Hydrazine-HNO_3	30	970	Impigement angle 120°
Hydrazine-N_2O_4	6	61	Nozzle diameter 1.5mm
A-50/NTO	8	13	Impigement angle 60°
UDMH - N_2O_4	11	34	Nozzle diameter 0.8mm

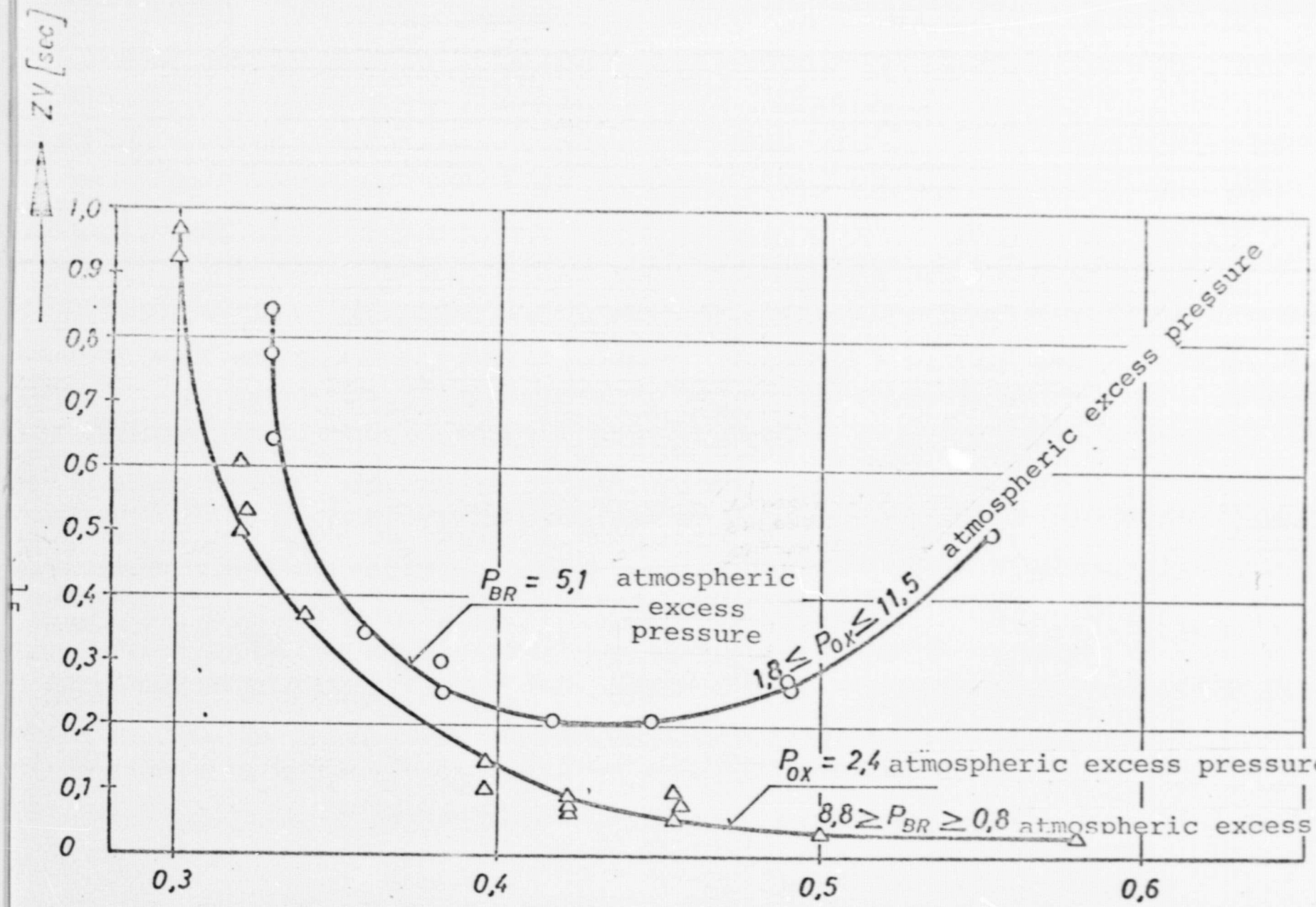
3. Ignition delay tendency at increasing injection pressure

Propellant combination	Oxidizer pressure rises P_{BR} = constant	Fuel pressure rises P_{OX} = constant	
[1]Hydrazine-HNO_3	ZV falls - rises	ZV rises	Fig 1
[1]Hydrazine-N_2O_4	ZV rises	ZV rises	Fig 4
[2]Hydrazine-N_2O_4	ZV falls	ZV no tendency	Fig 3
[3]UDMH-N_2O_4	ZV falls	ZV falls	Fig 5
[3]A-50/NTO-N_2O_4	ZV falls	ZV falls	Fig 5

[1] Impigement angle $\beta = 120^0$
Nozzle diameter D = 1.5 mm

[2] $\beta = 60^0$; D = 1.5 mm

[3] $\beta = 60^0$; D = 0.8 mm



Hydrazine-nitric acid.

Nozzle diameter, 1.5 mm

Nozzle angle, 120^0

Bild 1

1. Ignition delay of the propellant combination on hydrazine-nitric acid

Hydrazine-HNO_3

Nozzle diameter, 1.5 mm

Nozzle angle, 120^0

$\Omega = 0,4$

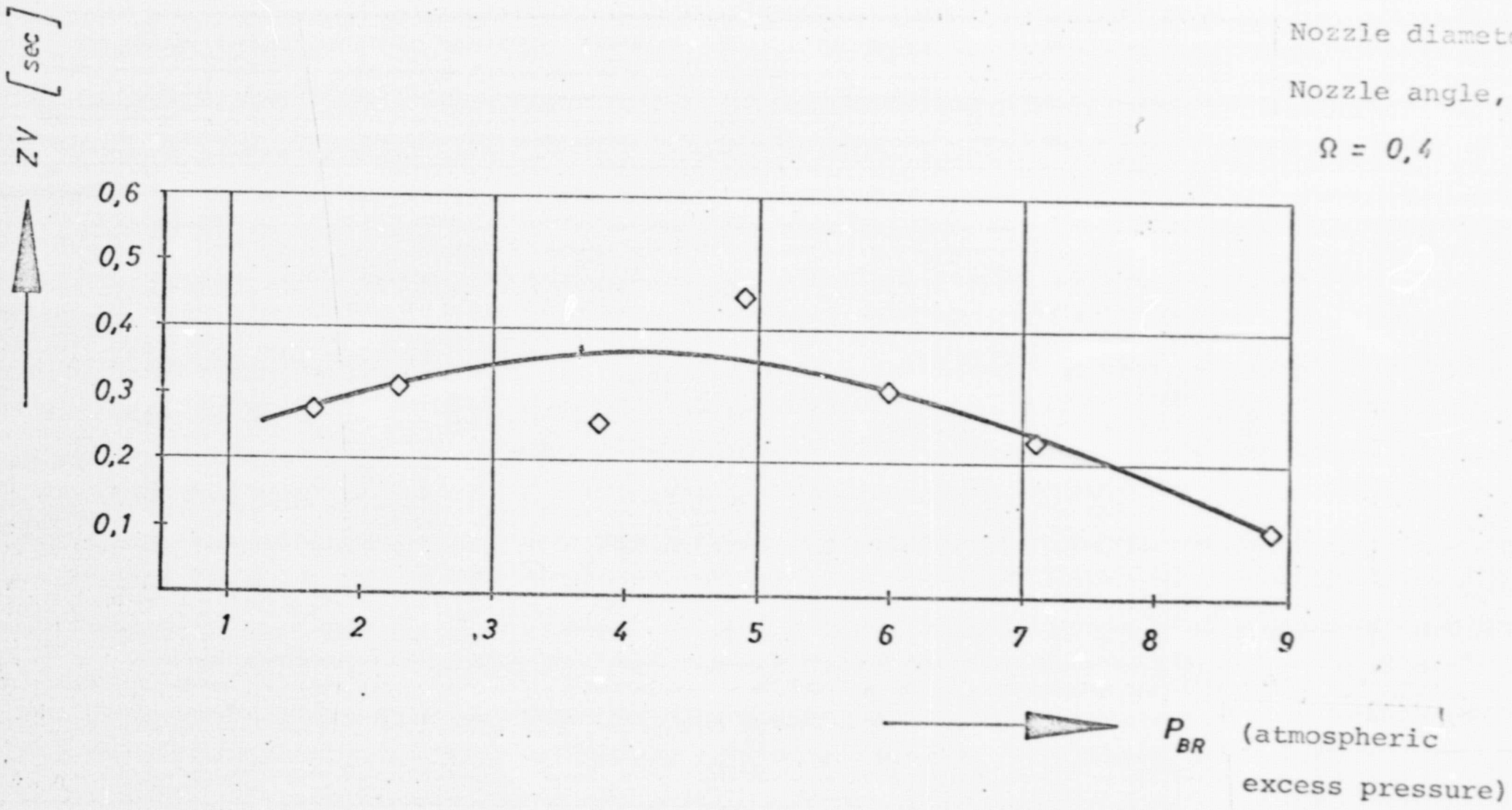


Bild 2

2. Ignition delay of the propellant combination hydrazine-nitric acid at constant mixture ratio

Hydrazine-N_2O_4

Nozzle diameter, 1.5 mm

Nozzle angle, 60^0

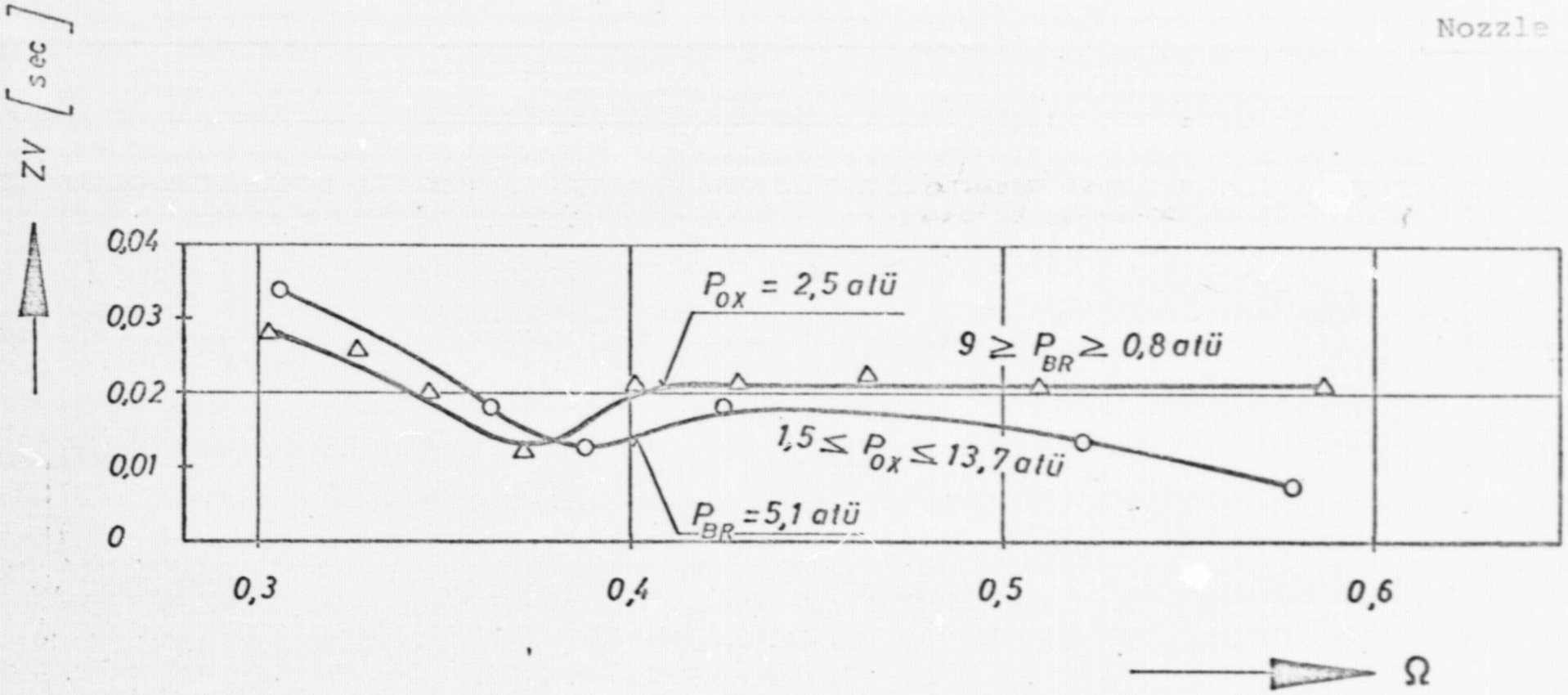


Bild 3

3. Ignition delay of the propellant combination hydrazine-N_2O_4 at an impingement angle of 60 deg

Hydrazine-N_2O_4

Nozzle diameter, 1.5 mm

Nozzle angle, 120^0

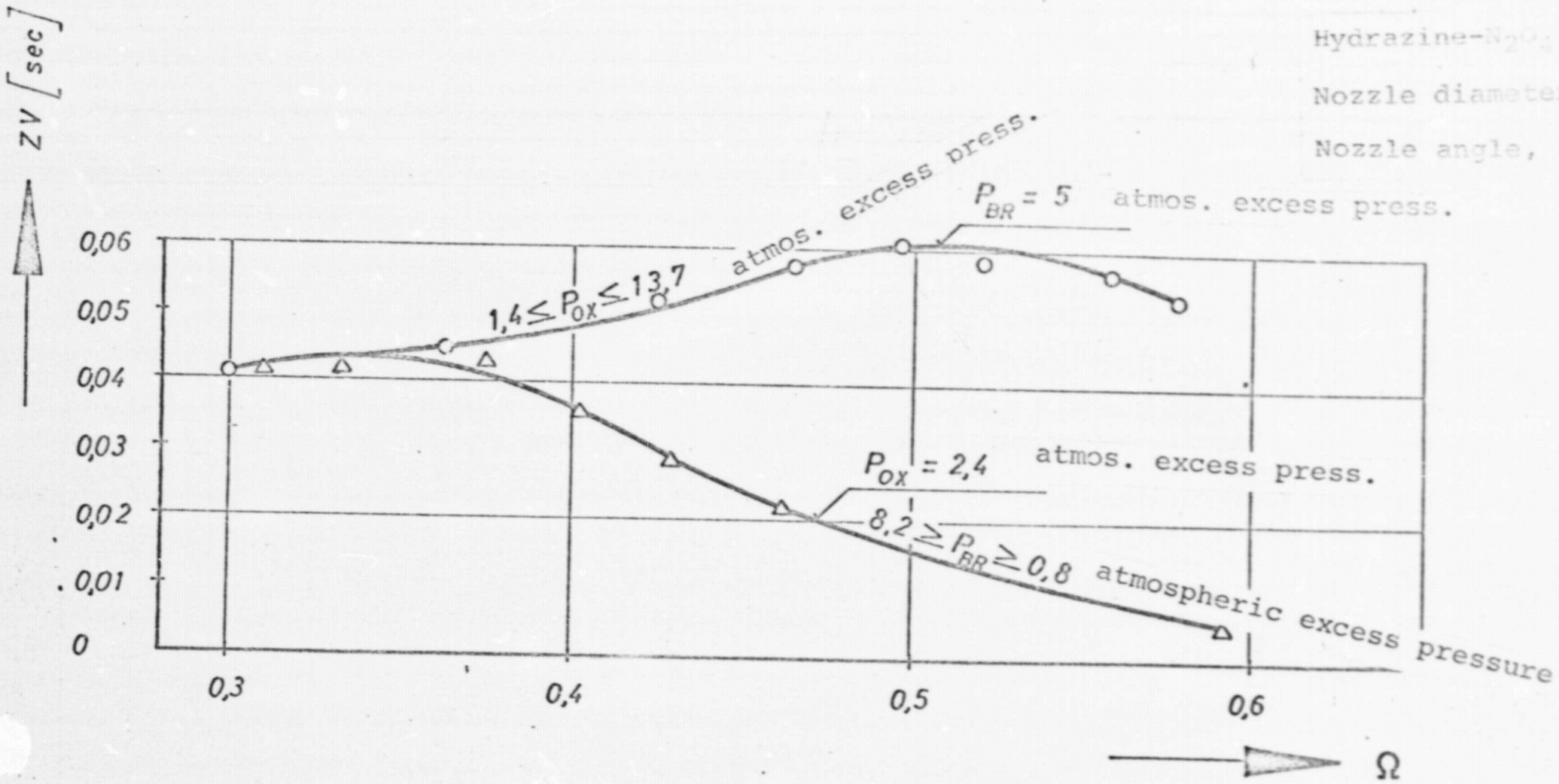


Bild 4

4. Ignition delay of the propellant combination hydrazine-N_2O_4 at an impingement angle of 120 deg

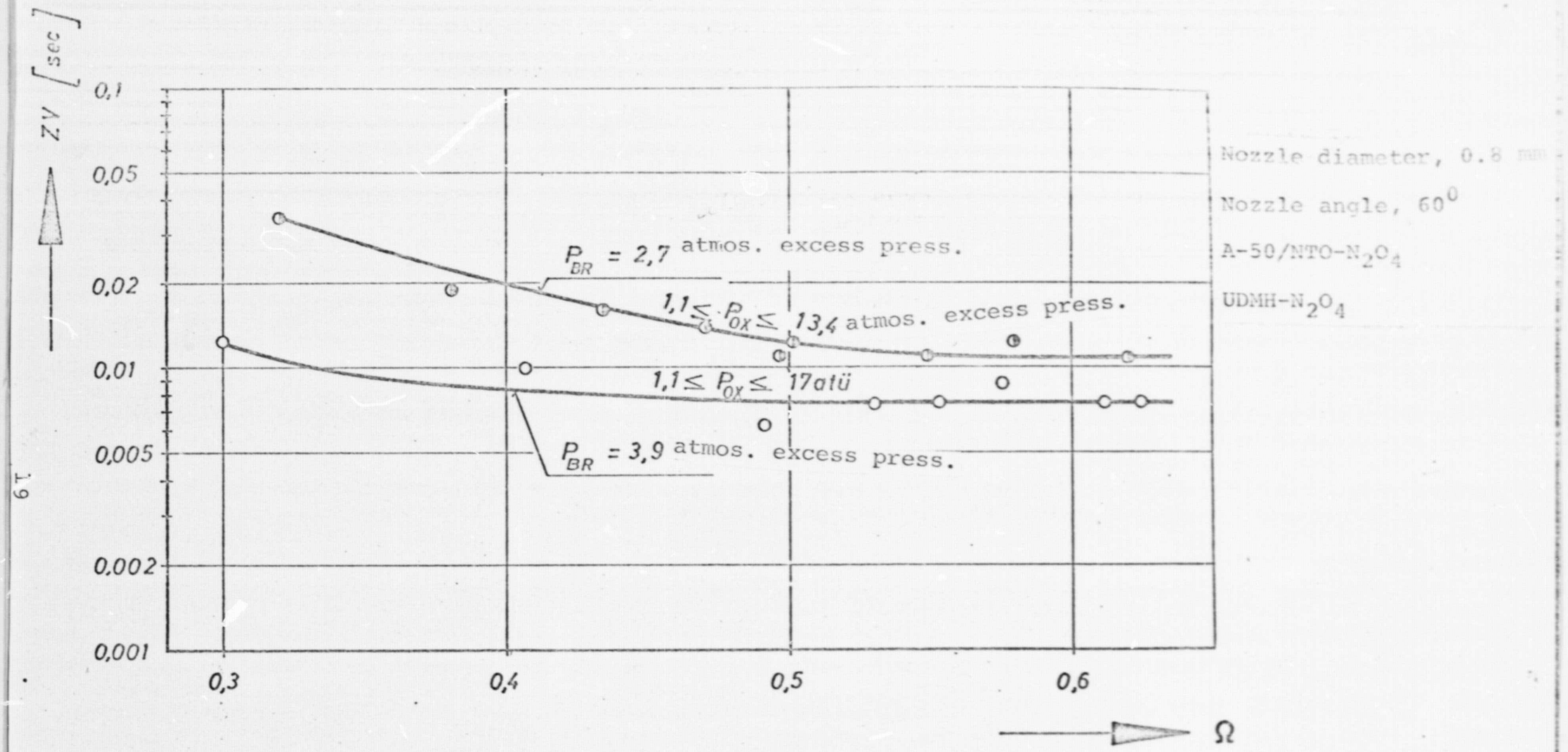


Bild 5

5. Ignition delay of A-50 and UDMH with N_2O_4

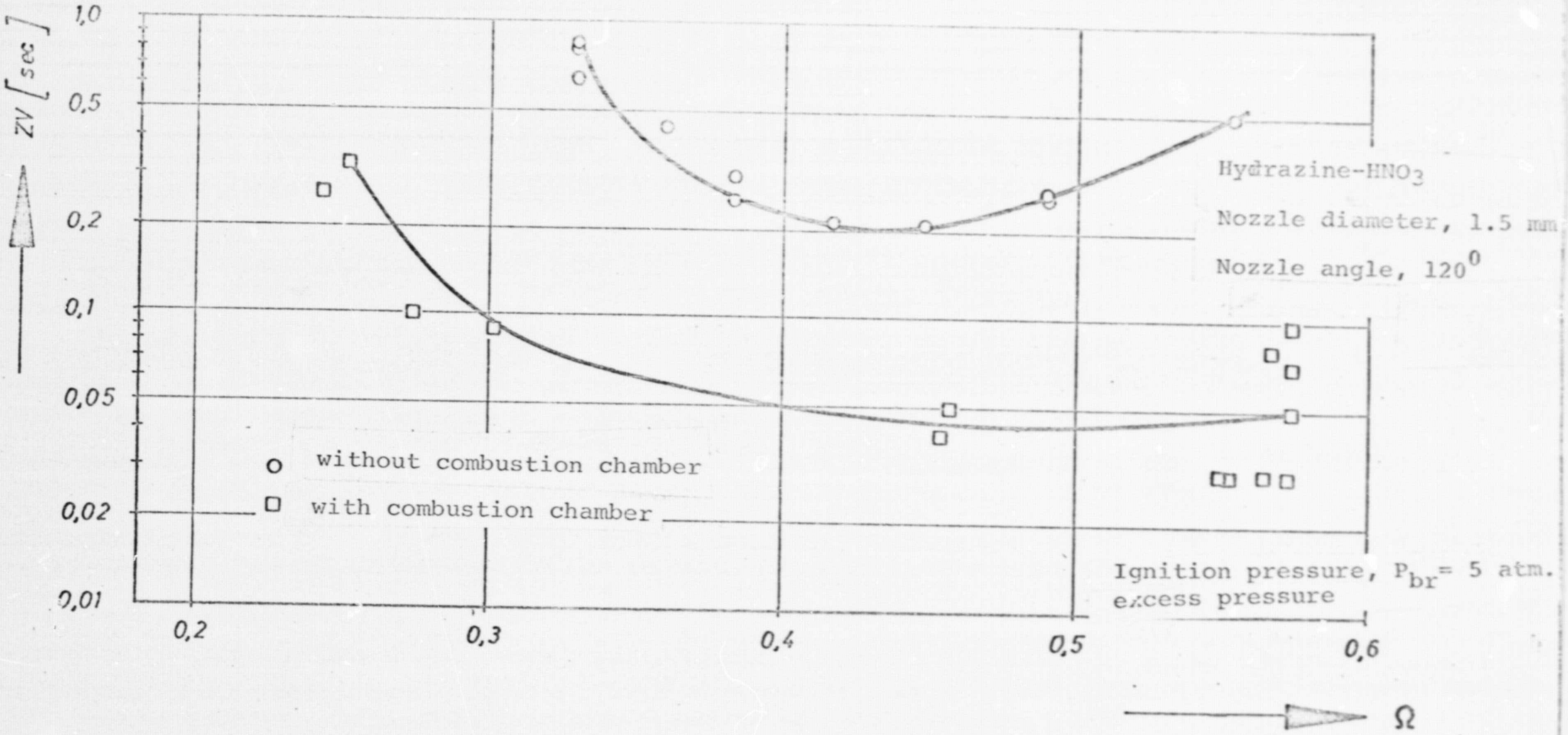
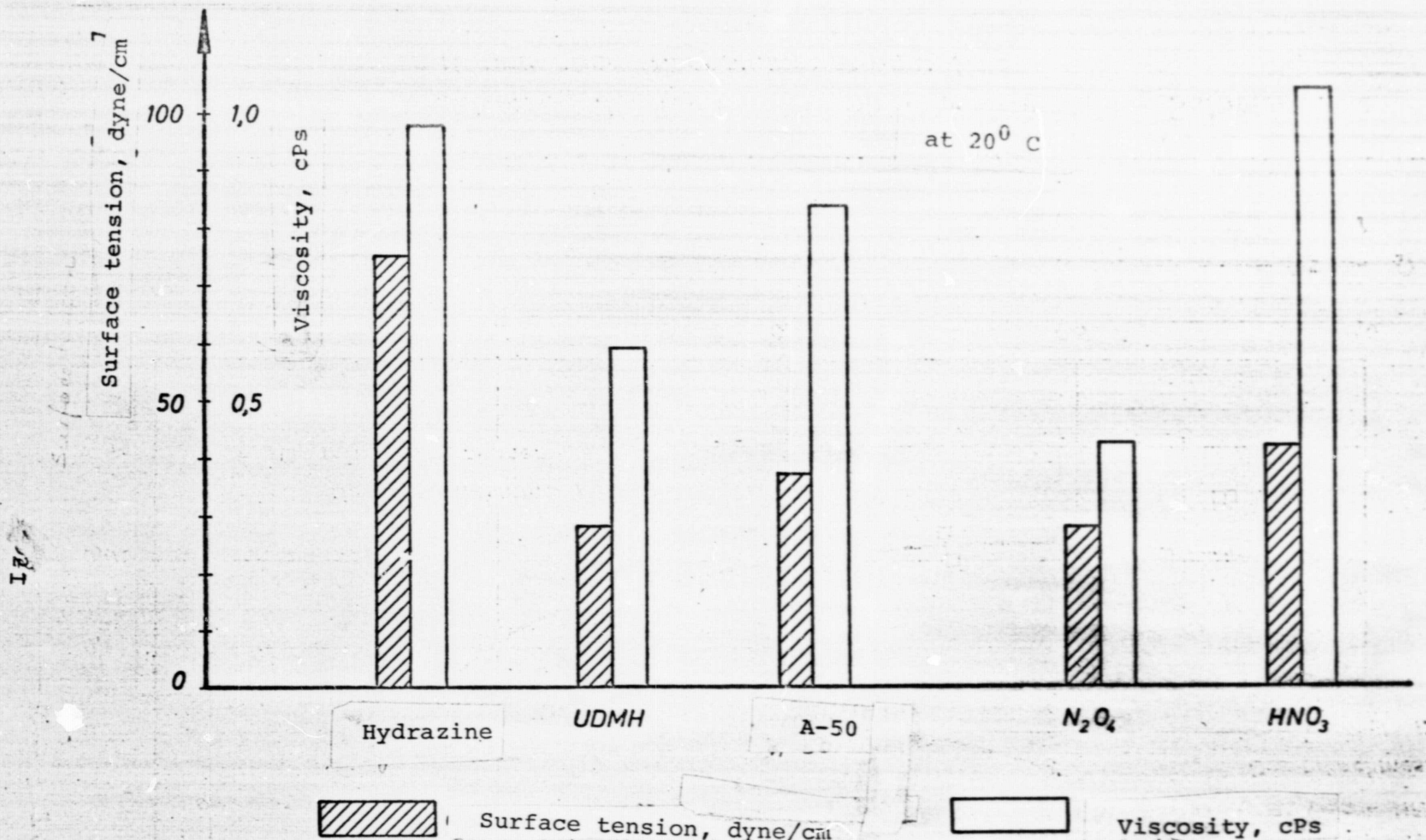
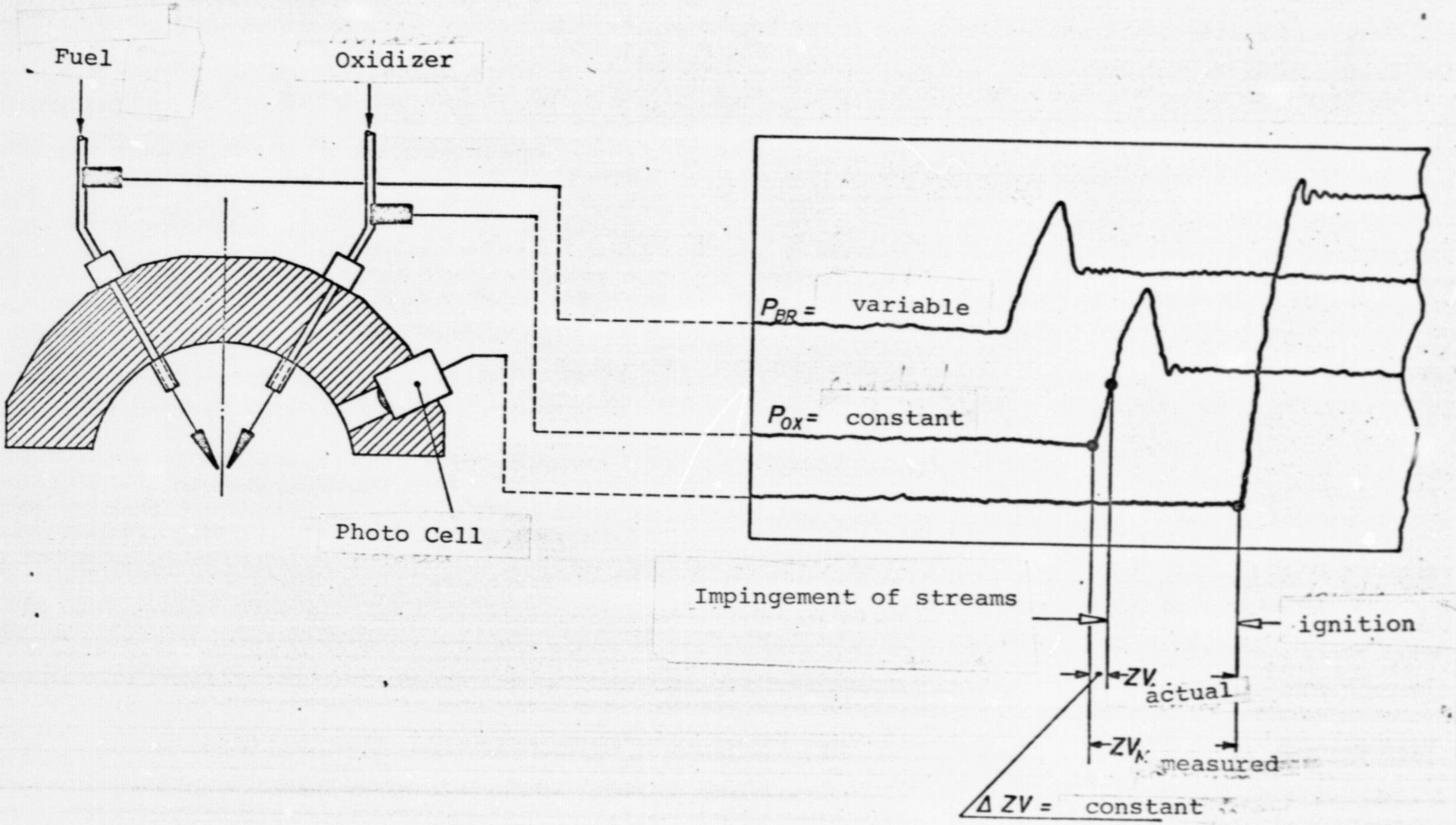


Bild 6

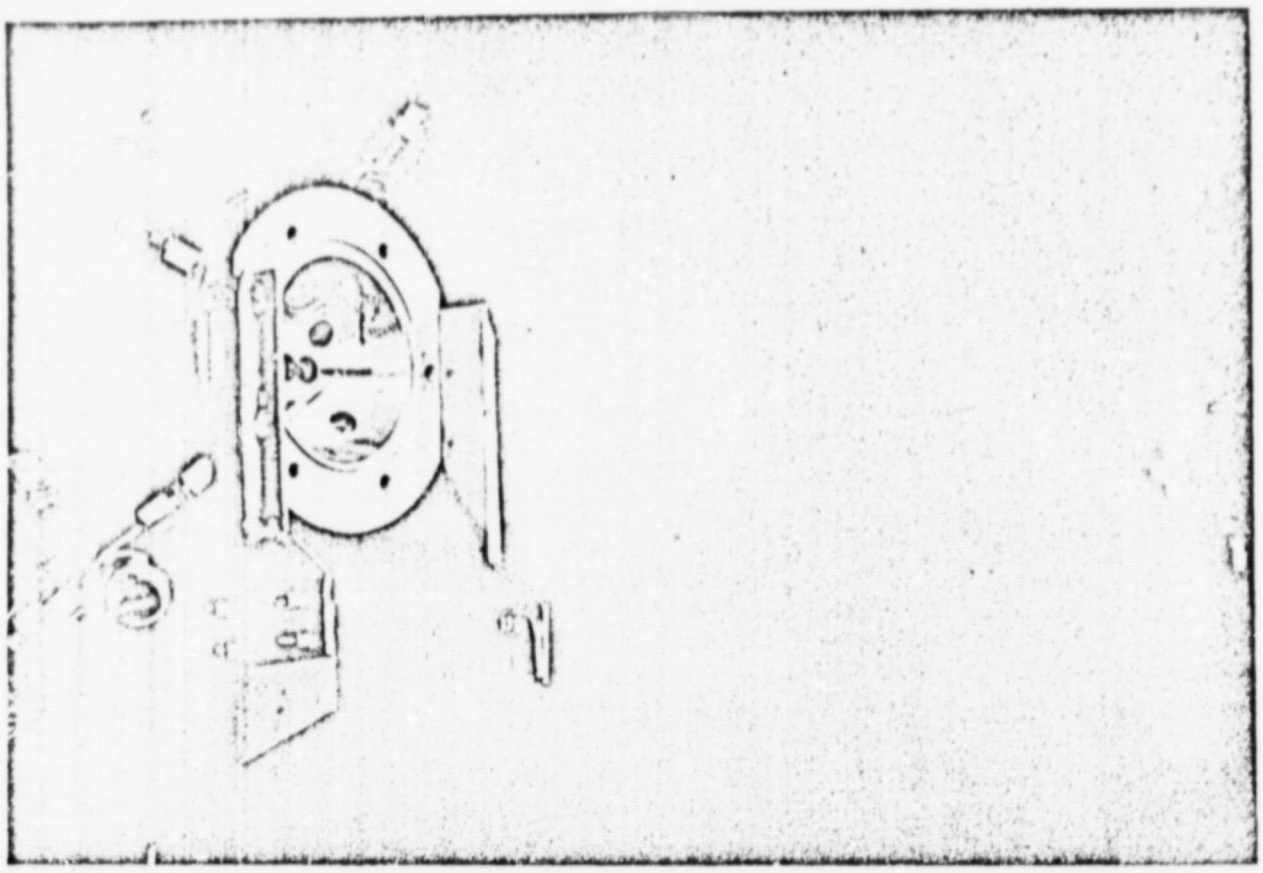
6. Ignition delay of the propellant combination hydrazine-nitric acid with and without combustion chamber shroud



7. Surface tension and viscosity of fuels and oxidizers

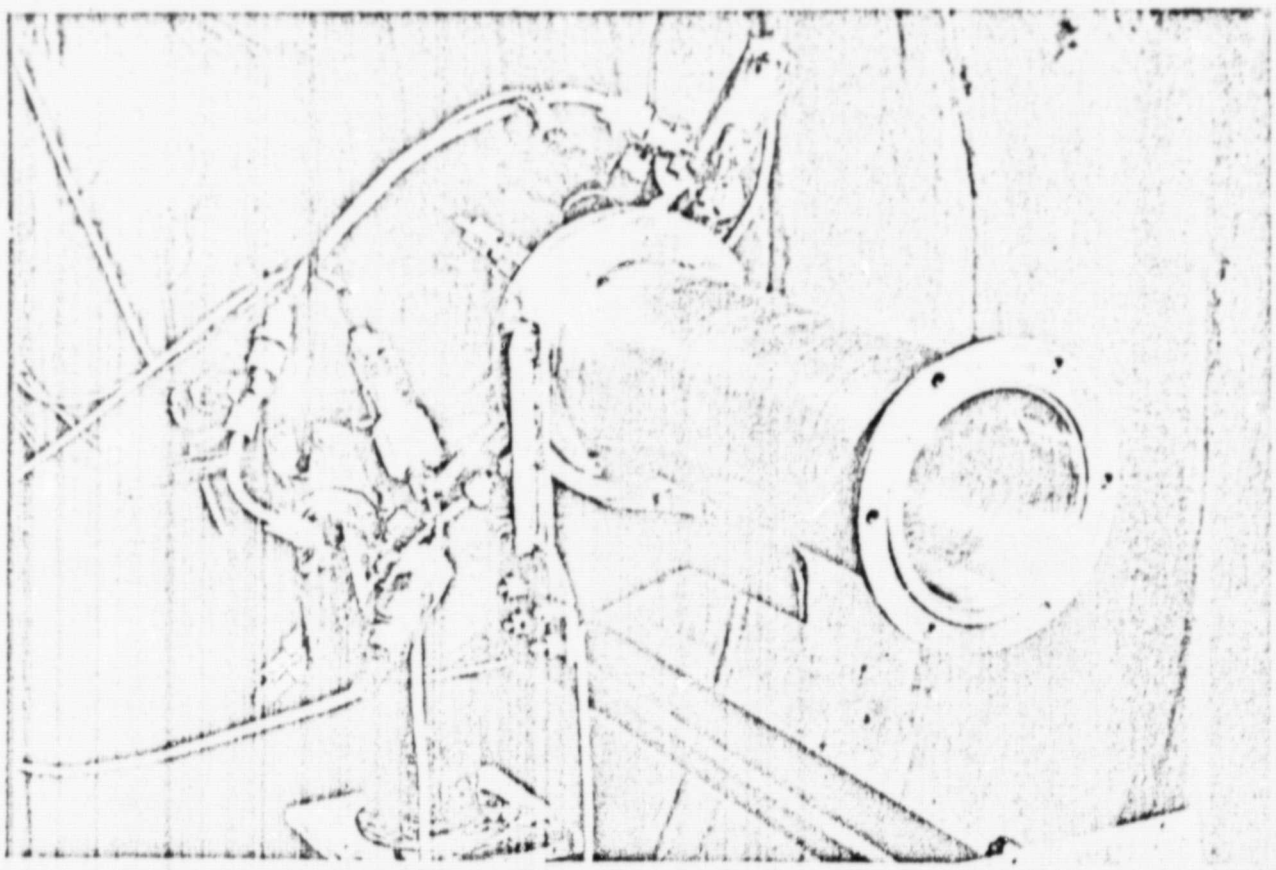


8. Ignition delay measurement diagram

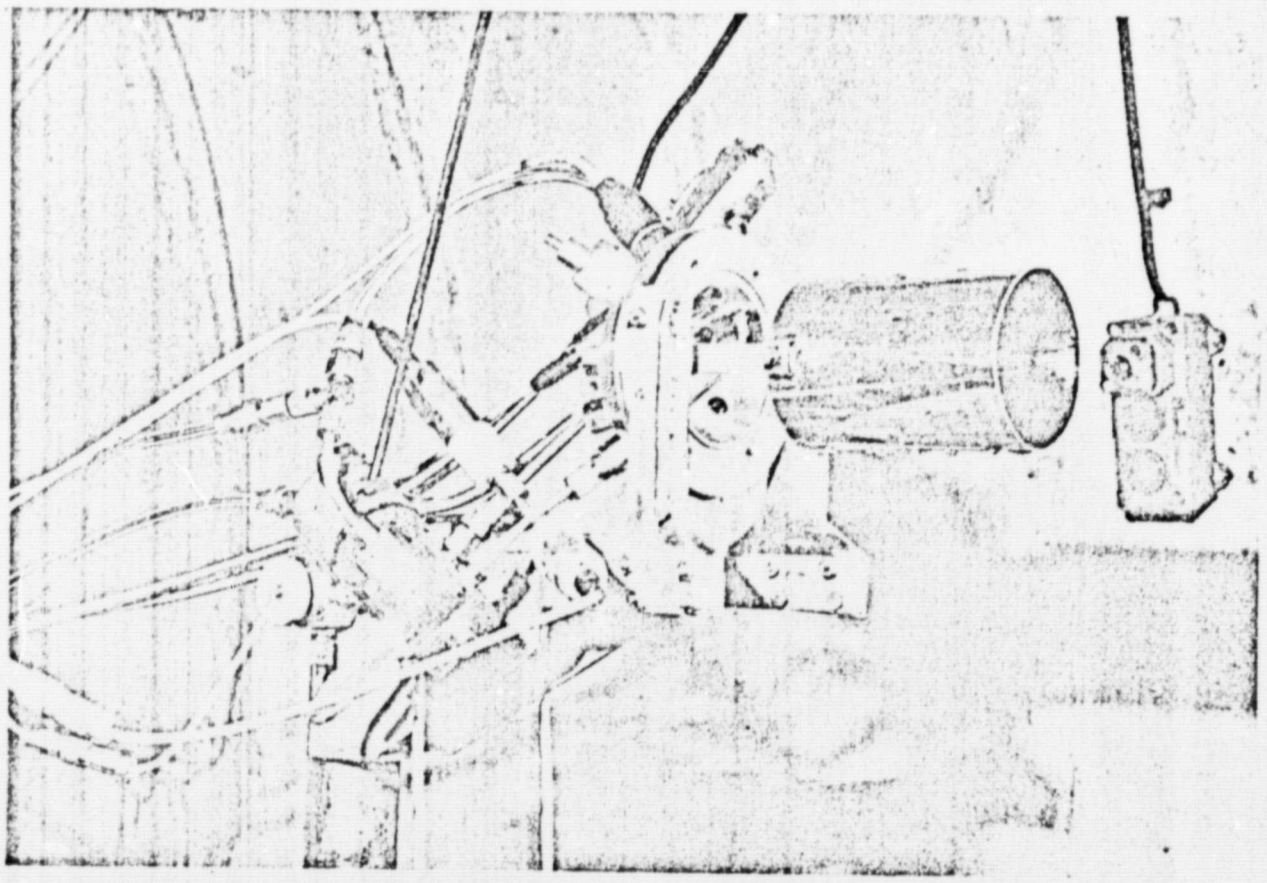


9. Ignition setup for hypergolic ignition in the impinging stream process

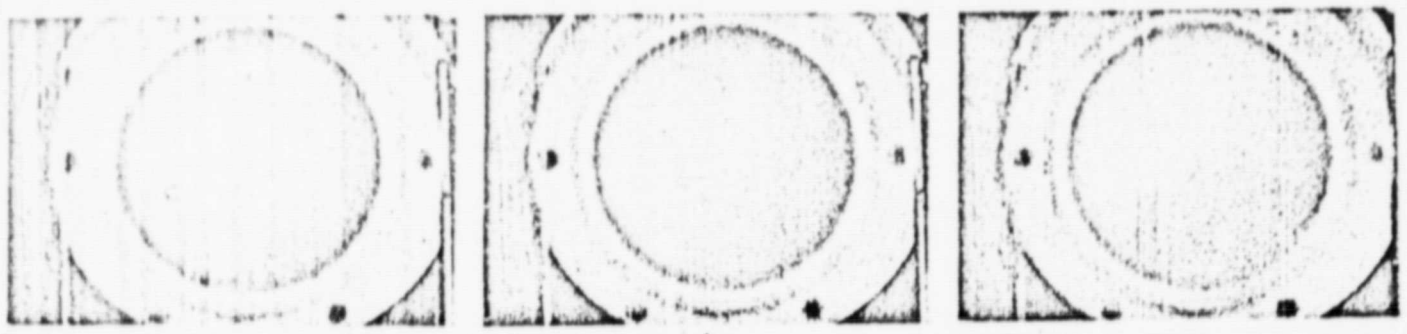
10. Incomplete reaction of hydrazine with nitric acid

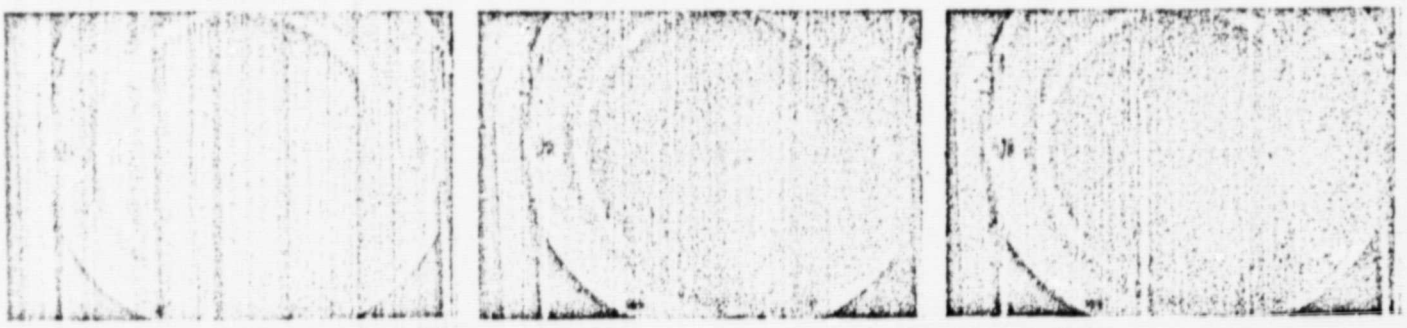


11. Ignition setup with mounted combustion chamber shroud



12. Ignition setup with adjustable combustion chamber shroud





13. Development of ignition on the combustion chamber wall